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ACTIVE CONTROL OF OSCILLATIONS IN SIMULATIONS OF GAS-TURBINE COMBUSTORS

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Abstract

The approach to extinction of a premixed methane-air flame stabilised behind a plane sudden-expansion gave rise to cyclic movement of the position of flame stabilisation with a period of the order of 100 ms. These oscillations have been quantified in terms of simultaneous measurements of pressure and light emission, and the pressure maximum corresponded to the flame position closest to the step and the minima to that furthest away. The active control strategy of imposing out-of-phase oscillations was unsuccessful since the period of the near-limit cycles varied over a substantial range and a new approach will be required to track the signal and to implement online actuation that will counteract the tendency for flame movement.

1. Introduction

Combustion oscillations have been studied extensively in laboratory-scale combustors, with emphasis on the large-amplitude acoustic oscillations that occur with near-stoichiometric mixtures of fuel and air by, for example, Sivasegaram and Whitelaw (1987) and Paschereit *et al.* (1998). These oscillations have been controlled with a variety of strategies, the most successful of which has been the feedback-driven imposition of out-of-phase oscillations on either the pressure field or the heat-release by, for example, Poinsot *et al.* (1989) and Lee *et al.* (1999).

Oscillations close to the flammability limits in small-scale combustors have received less attention but De Zilwa *et al.* (1999a) showed that the approach to these limits led to a cyclic longitudinal movement of the location of flame stabilisation with frequencies lower than those associated with acoustic modes and increasing with flow velocity. The pressure fluctuations associated with these oscillations were smaller than those with mixtures close to stoichiometric, but increased with the rate of heat release and, in the presence of an exit nozzle, due to amplification by the bulk-mode resonance of the combustor cavity.

This paper extends the knowledge of the nature of the oscillations close to the lean limit with emphasis on its implications for active control. The flow configuration was that of Khezzar *et al.* (1999) and active control was attempted with the controller of Hendricks *et al.* (1992).

The following section describes the flow configurations, measurement methods and control apparatus. The nature of the near-limit oscillations is then described and is followed by consideration of the implications of these results for control. The paper ends with a summary of the more important conclusions and their implications.

2. Flow configurations, instrumentation and control apparatus

The experiments were conducted in the plane sudden-expansion of figure 1, which comprised acoustically-open upstream and downstream boundaries. A 100 mm long, 3 mm thick quartz window mounted immediately downstream of the expansion plane provided optical access to the flame.

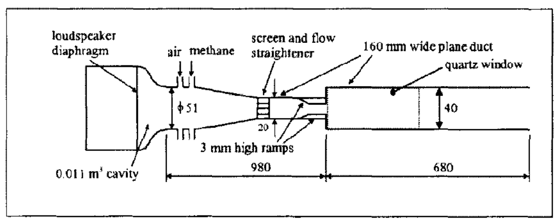

Figure 1: Plane sudden-expansion arrangement. Not to scale. All dimensions in mm except where indicated otherwise.

The pressure fluctuations in the combustor were measured by a water-cooled piezo-electric pressure transducer (Kistler 6121 with charge amplifier 5007) mounted on the wall of the duct 50 mm upstream of the expansion plane. The transducer signal was digitised (National Instruments PC-1200) and the near-limit oscillations characterised by the records of the pressure fluctuations. These oscillations were also examined in terms of a photomultiplier signal which was acquired at the same time as that from the pressure transducer. The photomultiplier gathered light emission along a line across the width of the combustor with a spatial resolution of 2 mm.

Active control by imposing oscillations with the loudspeaker at the frequency of, but out-of-phase with, the combustion oscillations was attempted with the controller of Hendricks *et al.* (1992) with a feedback signal from the pressure transducer.

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3. The nature of the near-limit oscillations

Isothermal plane sudden-expansion flow at all but very low Reynolds numbers was asymmetric with unequal regions of separation behind the two steps. Though combustion eliminated most of this asymmetry, the branches of flame behind the two steps extinguished independently. Immediately prior to the extinction of the first branch, both branches gave rise to a transverse flapping motion which has been characterised with a CCD camera by De Zilwa *et al.* (1999a), with frequencies less than 10 Hz and the pressure signals showed peak-to-peak variations that increased with flow rate up to around 0.2 kPa at a Reynolds number, based on velocity and equivalent duct diameter just upstream of the expansion, of 81,000. These small amplitudes made it difficult to distinguish the pressure fluctuations associated with the flapping motion from the background noise, and the signals were also complicated by the presence of pressure fluctuations associated with the out-of-phase movements of the two branches of flame which are shown in figure 2.

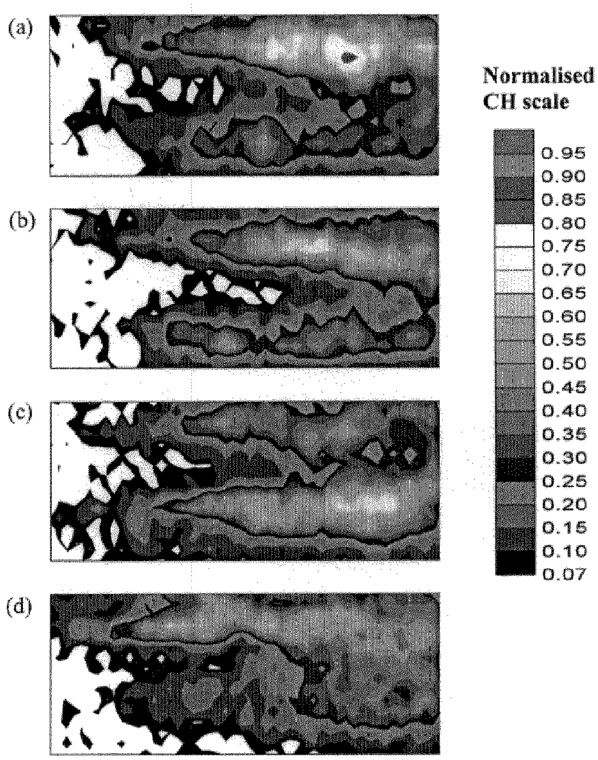

Figure 2: CH emission intensity distributions of the flame prior to the extinction of the first branch of flame. Reynolds number = 42,000, $\phi = 0.68$.
Sequence of images obtained at 60 ms intervals with an exposure time of 1 ms. Observation window height and length are 40 and 100 mm, respectively. CH values normalised by maximum.

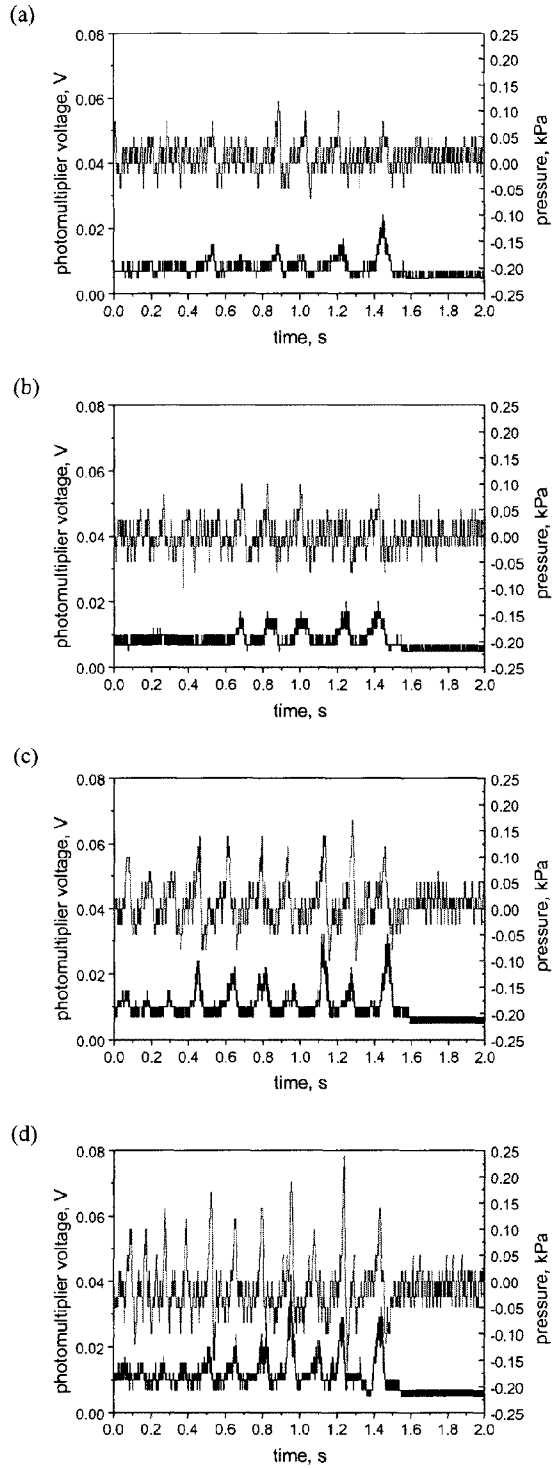

Figure 3: Simultaneous pressure transducer and photomultiplier signals at the lean extinction limit.
——— pressure signal low-pass filtered at 100 Hz,
——— light emission from photomultiplier focussed 10 mm above the bottom wall of the duct and 30 mm downstream of expansion.
Reynolds number: (a) 48,000, (b) 57,000, (c) 68,000 and (d) 81,000.

After the extinction of the first branch of flame, the remaining flame was comparatively stable behind one of the steps until the equivalence ratio was lowered further and extinction was preceded by a lateral and longitudinal oscillation which was also visualised by De Zilwa *et al.* (1999a). Traces of the pressure fluctuations at higher flow rates, at which the low-frequency oscillations can be readily distinguished from the background noise with the aid of low-pass filtering at 100 Hz, are shown in figure 3 for the period of around 1.5 s preceding and 0.5 s following extinction. The periodic nature of the signal prior to extinction is clear and the average frequency increased with flow rate from around 5.4 Hz at a Reynolds number of 48,000 to 7.5 Hz at 81,000. The amplitude of the pressure fluctuations also increased with flow rate, and hence with heat release, from a peak-to-peak value of around 0.15 kPa at a Reynolds number of 48,000 to 0.4 kPa at 81,000.

Though the average frequency of the oscillations increased with flow rate, the range encountered at each flow rate implied variations in the time taken to complete each low-frequency cycle. For example, figure 3c shows variations in the period of oscillation of between 0.1 s and 0.16 s. This variation in period was caused by the variation in the length of the region of separation, as expected in turbulent flows, and consequently in the distance travelled by the flame.

(a)

(b)

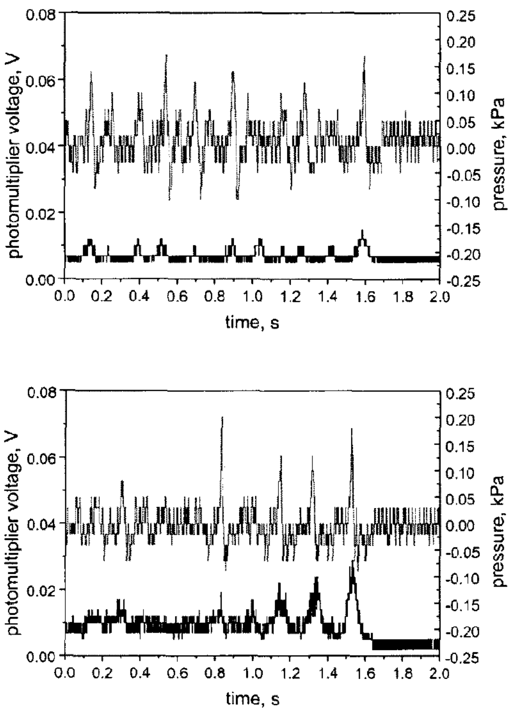

Figure 4: Simultaneous pressure transducer and photomultiplier signals at the lean extinction limit. Reynolds number: 68,000.
——— pressure signal low-pass filtered at 100 Hz,
——— light emission from photomultiplier focussed 10 mm above the bottom wall of the duct and (a) 15 and (b) 40 mm downstream of expansion.

All the pressure signals shown were obtained with the single flame stabilised on the bottom step. The signals obtained simultaneously from the photomultiplier which was focussed along a line 10 mm above from the bottom wall of the duct and 30 mm downstream of the step are also shown and the correlation between the two signals is clear with coincident maxima. Light was collected across the width of the combustor so that the influence of the lateral oscillation was minimised and this was confirmed by the correlation between the two signals being independent of the side of the duct on which the pressure transducer was mounted

Thus, the effect of the longitudinal oscillation was isolated and the correlation between the signals suggests that the strongest light was emitted at the pressure maxima. The light signals obtained from different downstream locations, figure 4, showed that, as expected, the maxima of the signals were smallest close to the step. They also showed that the spikes were wider when obtained further downstream, indicating increased residence time of the flame at locations further away from the step, and confirming the longitudinal motion of the location of flame stabilisation. The coincidence of the maxima of the two signals was independent of downstream position of photomultiplier, which suggested that the longitudinal movements of the flame gave rise to a strengthening and weakening of the entire flame, with the flame strongest when it was closest to the step, consistent with the CCD images of figure 2.

The pressure signals show gradual increases and more rapid declines which suggests different rates of travel of the flame before and after the pressure maximum. This is consistent with the mechanism of oscillation suggested by De Zilwa *et al.* (1999a) that extinction occurred due to strain rates and travelled downstream at the velocity in the shear layer, of the order of a few metres per second, and that the flame returned towards the step at the flame speed of the mixture in the recirculation zone, of the order of tens of centimeters per second. This again implies that the pressure maxima corresponded to the flame positions close to the step, with the sharp decrease when the flame moved downstream, followed by the more gradual increase as the flame moved more slowly back toward the step.

4. Feedback-driven control of the near-limit oscillations

The pressure signals obtained involved oscillations with frequencies less than 10 Hz as extinction was approached. The feedback controller used by Hendricks *et al.* (1992) and subsequently by, for example, Sivasegaram *et al.* (1995) and Bhidayasiri *et al.* (1998) to control the continuous large-amplitude acoustic oscillations that occur close to stoichiometry could not lock on to these lower-frequency oscillations. Indeed, none of the feed-back systems developed to deal with acoustic oscillations, including those of Langhorne *et al.* (1990) and Gutmark *et al.* (1992), which rely on determining a single dominant frequency and imposing an out-of-phase oscillation at that frequency are likely to control this near-limit oscillation. This is partly because the oscillation is transient and allows the controller very few cycles, usually less than twenty, within which to determine the dominant frequency and, more importantly, because the period of the oscillations varied by as much as 60 % from one cycle to another.

The low frequencies imply slow changes and hence, there may be time to track a characteristic of the flame and to take action in response to its magnitude or change in magnitude. The relative time-scales can be estimated for the most straightforward form of control that can be envisaged, which would involve tracking the pressure signal and imposing pressure oscillations that counteract the naturally-occurring fluctuations. The 3 ms delay for a pressure pulse to travel from an actuator located even a metre away from the flame is small compared with the oscillation period of around 100 ms, and suggests that tracking the signal in the time domain together with online actuation may be successful.

The near-limit oscillations were caused by the high strain rates close to the step and the downstream movement of the position of flame stabilisation along the shear layer till the strain rate decreased sufficiently to allow flashback of the flame. Thus it is necessary to counteract the downstream movement of the flame by reducing the strain rate or increasing the robustness of the flame at the instant at which it is most likely to detach by, for example, slowing the flow or by injecting fuel at this instant. A pressure transducer signal is usually the most convenient form of feed-back and, since the pressure maximum corresponded to the flame position closest to the step, actuation should take place just after this maximum to inhibit the downstream movement.

5. Concluding remarks

The pressure and light signals showed oscillations prior to extinction consistent with the cyclic downstream movement of the flame at the flow velocity in the shear layer, followed by a slower return toward the step at the flame speed of the mixture in the recirculation zone. The frequencies and the pressure fluctuations associated with these oscillations increased with flow rate up to around 7.5 Hz and 0.4 kPa at a Reynolds number of 81,000.

De Zilwa *et al.* (1999a) showed that these near-limit oscillations could give rise to much larger pressure fluctuations when there was a resonance frequency in the vicinity and that these increased amplitudes caused the flammability range to narrow. Hence, suppression or control of these oscillations is important. However, the feedback-driven active control strategy of determining the dominant frequency of the combustion oscillations and imposing out-of-phase oscillations was unsuccessful because the period of the near-limit oscillations varied by as much as 60 % from one cycle to another. It may be possible to track the variations in frequency, but it would be preferable to track a flame characteristic and take action at a particular instant in the cycle to counteract the flame movement.

6. Acknowledgements

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